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A Carge-discharge System of a Solar-Electric Vehicle

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태양광-전기자동차의 충전·방전 시스템에 관한 연구

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ABSTRACT

Design of an electric power system on the solar-electric vehicle is very important because sunlight intensity is changed by weather conditions and road environments. Power output of solar module on the vehicle being changed by unsteady sunlight intensity. In this paper, design method of an electric power system are proposed to generate steady electric power output. The test results shows the electric power system are effective because the solar-electric vehicle have steady driving speed under unsteady sunlight conditions.

Key Words : Solar-electric Vehicle(태양광-전기자동차), Charge and Discharge System(충전방전시스템), Electric Power System(전력시스템), Circuit Design(회로설계), Vehicle Design(자동차설계)

1. Introduction

Electric cars using photovoltaic cells have been researched to diversify the energy sources for vehicles and to meet the need for environmentally friendly vehicles. However, due to the low efficiency of photovoltaic cells, they still cannot be used as the main power source for vehicles, but they have been developed for research of single-person vehicles or for racing cars.[1,2] The efficiency of photovoltaic cells must be improved before they can be used as the main power source for vehicles. However, photovoltaic cells can be used to supply auxiliary electric energy for charging in hybrid or electric cars.

The output of photovoltaic cells varies greatly with the solar intensity and decreases sharply in weather conditions with low solar intensity (cloud, rain, morning, evening, night). This weather dependence is an additional constraint for using photovoltaic cells as a power source for vehicles. Even when a solar-electric vehicle travels in daylight, the solar intensity acting on the photovoltaic cells is highly irregular depending on the shape of the clouds in the sky. Moreover, street trees and various artificial objects around the roads hide the sunlight, creating

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shade on the roads. The power system should be designed to generate relatively uniform voltages in the photovoltaic cells so that solar-electric vehicles can operate normally even in such irregular weather and road conditions.

2. Driving Situation of Solar-Electric Vehicles

2.1 Changes in solar intensity due to weather conditions

The solar intensity that photovoltaic cells receive varies greatly by latitude and local environment and by season and weather conditions even at the same latitude.[3] Above all, the solar intensity varies greatly by season: it is high in summer and low in winter. However, in summer, the efficiency drops slightly because the atmospheric temperature is high and the temperature of photovoltaic cells rises due to the intense sunlight. In other words, even if the solar intensity is the same, the power output decreases if the temperature of the photovoltaic cells is high.

There are a wide variety of clouds depending on the weather conditions. On a cloudy day with clouds all over the sky, the power output drops significantly because the photovoltaic cells receive hardly any sunlight. Therefore, when the sunlight is fully hidden by clouds, when there is almost no sunlight in the morning and evening, and during the night, additional batteries should be installed to secure electric energy required for driving. When the clouds in the sky are scattered, the power output of photovoltaic cells increases when they receive sunlight and decreases sharply when the sunlight is hidden by clouds. Therefore, in this weather condition, the power output of photovoltaic cells changes suddenly and irregularly. As a countermeasure, batteries are required to store the power produced from the photovoltaic cells while the sun is shining, and the car should drive with the power stored in the batteries when the power output decreases.

2.2 Changes in solar intensity on the road

When driving in the daytime on a sunny day without clouds, solar-electric vehicles can pass roads with landscape trees and artificial structures (e.g., high buildings, bridges, underpasses, tunnels) that can hide sunlight, which is the energy source, as shown in Fig. 1. Particularly in downtown areas, there are numerous street trees and artificial structures beside roads that block sunlight and generate shade on the roads. The power output of photovoltaic cells decreases sharply when solar-electric vehicles are in the shade of street trees and buildings while driving on the roads. The power output increases when the solar-electric vehicles receive sunlight and decreases sharply when they are hidden from sunlight by artificial structures or street trees. In this road condition, the power output of photovoltaic cells fluctuates quickly and irregularly. Furthermore, when there are consecutive buildings beside the road, the shaded areas on the roads become extended, creating sections where photovoltaic cells cannot produce enough power for driving. When the vehicles pass through long underground tunnels in mountains and downtown areas, the photovoltaic cells cannot receive sunlight for a long period. Hence, photovoltaic cells can produce almost no power inside tunnels. As a countermeasure, batteries that can store power produced by photovoltaic cells while the sun is shining are required, and the system should be designed to drive with the power stored in the battery in sections with low power output.

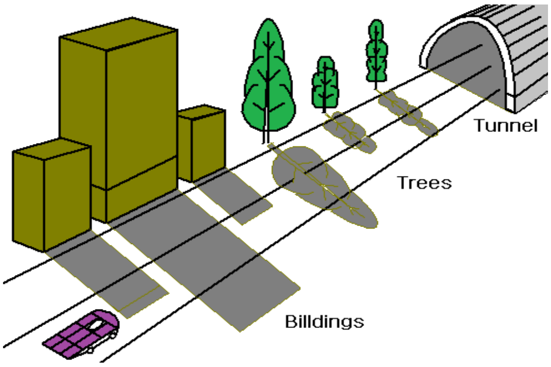

Fig. 1 The solar-electric vehicle on a road

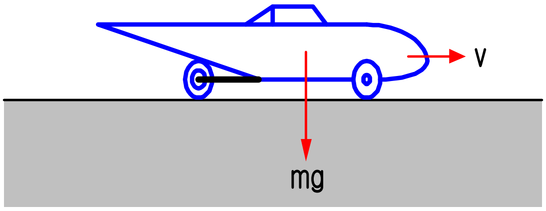

Fig. 2 Driving of the solar-electric vehicle

3. Power System Design

3.1 Prediction of power requirement

When a solar-electric vehicle runs on a flat road at a constant speed, as shown in Fig. 2, the energy required for driving can be determined as follows:[4-5]

$$P_{driving} = (\mu_{rr} mg + \frac{1}{2}\rho A C_d v^2)\frac{v}{\eta_e \eta_m} \qquad (1)$$

μ_{rr} : coefficient of rolling resistance
m : mass
g : acceleration of gravity
ρ : air density
A : frontal area
C_d : drag coefficient
v : vehicle speed
η_e : electrical efficiency
η_m : mechanical efficiency

The above equation shows that the design of a solar-electric vehicle should minimize the rolling resistance, vehicle weight, front projected area, and air resistance coefficient while maximizing the electrical efficiency and mechanical efficiency. Eq. (1) is the most basic energy relationship equation for determining the output from the photovoltaic cells of a solar-electric vehicle. Besides an electric motor for driving the solar-electric vehicle, there are various electric components in the vehicle, and their power requirements must be added. In addition, it is necessary to secure power required for acceleration and additional spare power. Thus, the power generated from the photovoltaic cells can be expressed as the following Eq. (2).

$$P_{solar} = P_{driving} + P_{accessary} + P_{aux.} \qquad (2)$$

Fig. 3 shows a graph representing Eq. (1) for the power requirement of a solar-electric vehicle at different weights and speeds. An air temperature of 20℃, a front projection cross-sectional area (A) of 0.961 ㎡, an electrical efficiency (η_e) of 0.92, and a mechanical efficiency (η_m) of 0.975 were applied. The total vehicle weight including one driver is approximately 200–300 kgf.

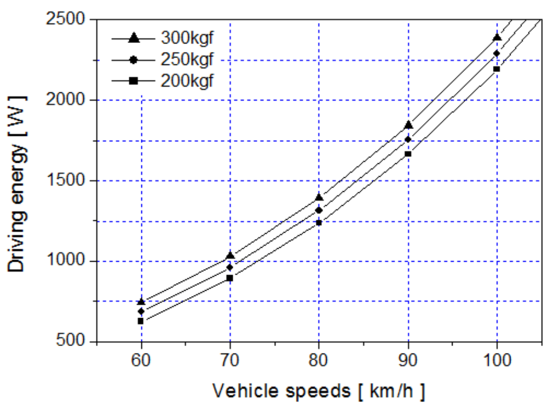

Fig. 3 Driving power and vehicle speed

When the driving speed of the vehicle is 100 km/h, the energy required for driving the vehicle is in the range of 2,100 – 2,400 W. If the output of the photovoltaic cell is approximately 1,300 W, as shown in Table 1, the maximum speed of the vehicle can be predicted to be approximately 80 km/h. In fact, approximately 20 – 30% of additional power should be secured considering additional energy demands for acceleration and electric components. Therefore, the power of Eq. (2) should be produced from photovoltaic cells. In addition, it can be seen that more energy is required to increase the vehicle speed in Eq. (1) and Fig. 3, but photovoltaic cells are installed at the top of the vehicle. Therefore, the installation area and the power that can be generated in photovoltaic cells are limited.

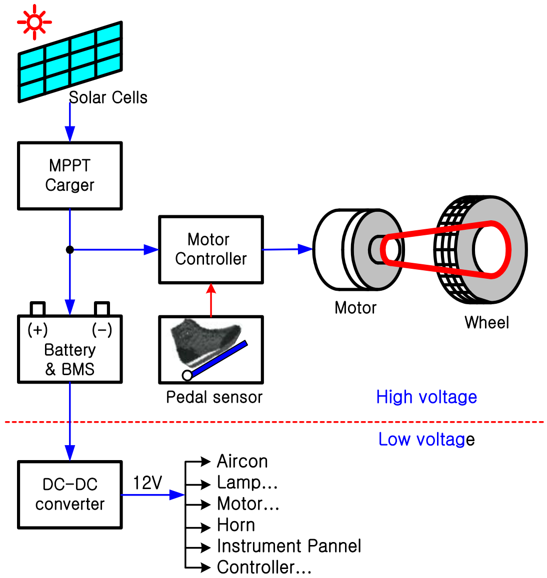

Fig. 4 Diagram of power system design

3.2 Power system design

The different parts of the power system of a solar-electric vehicle (i.e., the high-voltage part used in photovoltaic power generation and vehicle driving and the low-voltage part used for operating various electric components) should be designed separately, as shown in Fig. 4. In particular, the low-voltage system is very effective because it can use various DC 12V electric components used in existing vehicles.

First, in the high-voltage (system voltage) part, the voltages of the drive motor and battery should be identical, and the power generation voltage of photovoltaic cells must be slightly higher than the battery voltage. The power generated in the photovoltaic cells should be used for electric energy to drive the motor through a charge controller that includes a battery management system (BMS), and the remaining power should be used for battery charging.[6] The total power capacity of the photovoltaic cells should be adjusted by combining photovoltaic cells in a series and in parallel considering the system voltage and total operating current. In the low-power part, the existing electric components of the vehicle such as the DC 12V, various lamps, instrument panel, and horn should be used, and the high voltage should be lowered to low voltage (DC 12V) using a DC – DC converter.

3.3 Photovoltaic cell and MPPT combination design

Once the system voltage of the high-voltage part of the solar-electric vehicle power system is determined, the total output should be determined by combining photovoltaic cells in series and in parallel. Then, the electric circuit for the high-voltage part including a maximum power point tracker (MPPT) should be designed. The MPPT is controlled to operate the output of photovoltaic cells at the maximum power point (MPP) by driving the switching device of the internal converter circuit.[7-8] Fig. 5 shows the electric circuit structure of the power system. Fig. 5 (a) shows a structure where a module is constructed by serially connecting multiple photovoltaic cells to achieve the system

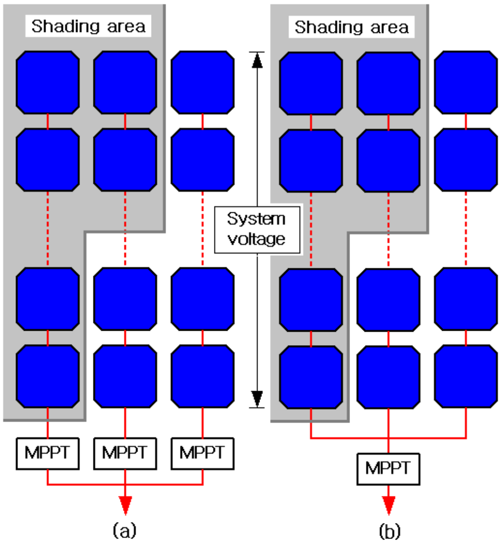

Fig. 5 An electric circuit of solar cells and MPPT

voltage required by the power system, and then the MPPT is connected to each photovoltaic cell module. In addition, multiple combinations of photovoltaic cell module and MPPT are connected in parallel to increase the operating current.

Fig. 5 (b) shows a structure where a module is constructed by serially connecting multiple photovoltaic cells to achieve the required system voltage. Multiple modules are connected in parallel, and then one large-capacity MPPT is used. As discussed in Section 2, when the vehicle passes through irregularly shaded areas due to scattered cloudy weather or street trees/artificial structures beside the road, multiple photovoltaic cell modules produce different power outputs. Therefore, in the case of (b), modules with different potential differences are connected in parallel, in which case the current can flow from a high-voltage module to a low-voltage module. According to the circuit design method of (a), even when a low voltage occurs in a module, it is raised to the system voltage by the MPPT, resulting in relatively identical potential differences overall. Therefore, the possibility of current flowing from a high-voltage photovoltaic cell module to a low-voltage module decreases. In the case of (b), a blocking diode may be installed in each photovoltaic cell module to prevent the current backflow. However, even in this case, the power from the low-voltage module cannot be supplied. In the case of (a), power can be supplied even if the power is weak because the low voltage of a module can be raised by the MPPT. Therefore, for solar-electric vehicles, it is more efficient to design an electric circuit that connects an MPPT to each module using the power system of (a).

4. Experiment, Results, and Discussion

The electrical specifications of the power system applied to the experimental solar-electric vehicle are listed in Table. 1. The voltage of the power system of the experimental vehicle is 48 V, and the total capacity of the photovoltaic cells is 1,336 W. As shown in Fig. 6, they were arranged on top of the vehicle to better receive sunlight. The photovoltaic cells were placed above the driver's seat to maximize their installation area. An auxiliary battery was installed to offset the rapid output drop of photovoltaic cells when the solar-electric vehicle passes through shaded areas.[9] Thus, the power charged in the battery is used when the output of photovoltaic cells drops or during acceleration. The low-voltage electric components using the DC 12V include the turn signals, brake lights, horns, and instrument panel. The power source for the DC 12V is supplied from a DC–DC converter.

Fig. 7 shows measurements of the charge and discharge voltages of the battery when the solar-electric vehicle runs at approximately 50 km/h or less in irregular sunlight conditions (road shaded by roadside trees and buildings). The upper graph shows the output voltage of the photovoltaic cells and the lower graph shows the battery voltage. The battery voltage dropped rapidly at the start because the power consumption of the drive motor increased sharply during the start and acceleration of the vehicle at a low solar intensity. In low solar intensity conditions (16–21 min, 26–33 min, and 38–42 min), the battery voltage dropped because battery power was additionally consumed due to the low output of the photovoltaic cells. Furthermore, in high solar intensity conditions (9–15 min, 23–24 min, around 35 min, 45–54 min), the voltage output of the photovoltaic cells increased, as did the battery voltage, because the power remaining after consumption in the drive motor was charged in the battery. The voltage difference between the photovoltaic cells and the battery was maintained at approximately 2 V.

The above experimental results show that even if the solar intensity is irregular, the proper voltage above the system voltage can be maintained while the battery is continuously charged and discharged, and the solar-electric vehicle can drive normally. However, if the output of the photovoltaic cells drops further, the vehicle speed can decrease, and it becomes impossible to drive later because the energy charged in the battery is consumed continuously.

Table 1 Electrical specifications of the experimental solar - electric vehicle

System voltage	DC 48V
Motor	5kW, 48V BLDC motor
Battery	DC48V, 30AH, Li-Polymer
Solar cell power	1,336W, 400 cells
Solar cell spec.	3.34W, 5.83A, 0.574V
DC-DC converter	DC 48V to DC 12V
DC 12V parts	Lamps, Horn, Instruments
Dimension	L5.0m × W1.8m × H1.1m
Weight	250kgf(include 1-person)

Fig. 6 Driving test of the solar-electric vehicle

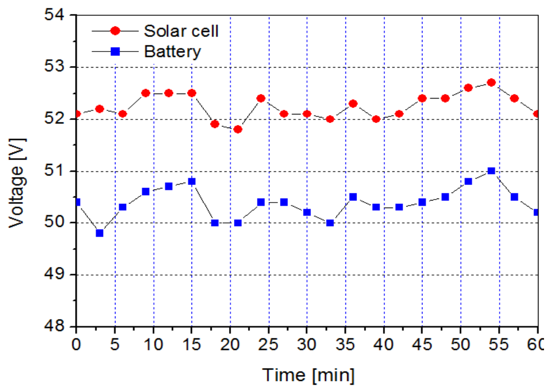

Fig. 7 Solar cell voltage and battery voltage during vehicle driving

5. Conclusions

Various weather conditions (particularly scattered clouds) during the driving of solar-electric vehicles cause irregular solar intensities to reach the photovoltaic cells. Furthermore, the roads on which the vehicles run are shaded by roadside trees, buildings, bridges, tunnels, and other artificial structures, causing uneven power generation of the photovoltaic cells and voltage differences between photovoltaic cell modules. To solve the problem of power drops of the photovoltaic cells due to irregular solar intensities, the batteries need to be installed in parallel, and the power system should be designed in such a way that the voltage in the photovoltaic cells is kept higher than the system voltage. Charge and discharge experiments were performed during the driving of a solar-electric vehicle in irregular sunlight conditions considering the above power system design conditions. The experimental results showed that even when the output voltage of the photovoltaic cells was uneven, the test vehicle could be driven normally because the charge and discharge functions of the power system worked effectively. Therefore, the proposed design method of a solar-electric vehicle considering solar intensity was found to be appropriate.

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